Modeling of Positive Leader Speed Under Slow Front Voltages—Part I: Long Air Gaps

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***Abstract*—This paper introduces a new mathematical model of positive leader propagation speed based on intense ionization in a thin boundary layer ahead of the tip of the leader channel. The model explicitly accounts for the effect of overvoltage and the resulting increase in leader current on leader speed. The model was applied to large rod-plane gaps under critical switching impulses. Numerical assessment of the model findings is included and whenever possible comparison with experiments has been found satisfactory.**

***Index Terms*—Air gaps, leader, streamer, switching impulses.**

I. Introduction

INVESTIGATION of the mechanism of positive leader propagation under slow front voltages is of great importance for basic understanding and practical applications in such phenomena as switching impulse breakdown of long air gaps [1]. The leader is basically an arc-like discharge with a voltage gradient that decreases with current and also with leader length or life time. Experiments by Les Renardières Group [2] on long air gaps under positive switching impulses of critical fronts showed positive leader currents in the range of 0.5–1.0 A and propagation speeds of 1–2 $\mathrm{cm}/\mu\mathrm{s}$.

Extensive investigations of the development of the positive spark in long air gaps, including the leader propagation phase, have been reported in [3]. Despite the merits of the model, presented as self-consistent, it still has some limitations: The work is based on detailed modeling by Gallimberti of an idealized single filament streamer. Furthermore, practical application involves a seemingly arbitrary choice of the number of filaments to obtain the real streamer charge. It is also noted that the number of filaments needed varies with experimental conditions. Although the model succeeds to account for several experimental facts, it was not as successful in predicting the effects of overvoltages on the final jump. Finally the model could only account qualitatively for the effect of overvoltages on positive leader speed for gaps even in the limited range of 4 m to 10 m.

A detailed investigation of thermal effects in air in the vicinity of the positive leader tip was reported in [4]. It was found that air heating in front of the leader tip could not account for the temperature range of 1500 K to 2000 K required in [3] for leader formation. Although the model described in [4] provided insight into some of the physical processes taking place near the tip of the leader, the leader speed was taken from measurements and could not be predicted from the model.

It is observed from the above that there is a real need for a model for positive leader speed suitable for engineering applications. The model should be capable of accounting for the effects of overvoltage and the resulting currents on positive leader speed. Although several simplifications will necessarily be introduced as explained below, the model must conform to known facts about the physics of the discharge phenomena involved.

II. Model Formulation

Leader propagation can only be sustained by appropriate current produced by streamer discharge (leader corona) which in turn is coupled to the electric field downstream from the leader tip. Criteria for positive leader formation and propagation have been formulated in [5]. Conditions at the leader tip are governed by the electric field due to the applied voltage which is opposed by the positive space charge field produced by leader corona. The effect of the space charge field is so substantial that it can completely shut down ionization phenomena in the leader tip zone (dead time).

In [5], the two criteria adopted for continuous leader formation and propagation are:

1) For stem formation, the streamers (leader corona) have to attain a critical size characterized by a streamer charge Q_0 related to the leader inception voltage by

$$Q_0 = c \cdot U_{lc} \tag{1}$$

where U_{lc} is the continuous leader inception voltage and c is a constant independent of the gap length.

2) For continuous leader propagation, the resultant electric field E_0 at the leader tip has to reach a critical value E_c, i.e.,

$$E_0 = E_{app} - E_{sc} = E_c \tag{2}$$

where E_{app} is the field due to the applied voltage and E_{sc} is the field due to the streamer space charge.

Since during continuous leader propagation resultant field conditions at the leader tip must be such that extinction of any streamer can be immediately replaced (second corona), we will in this model require that

$$E_c = E_{ci} \tag{3}$$

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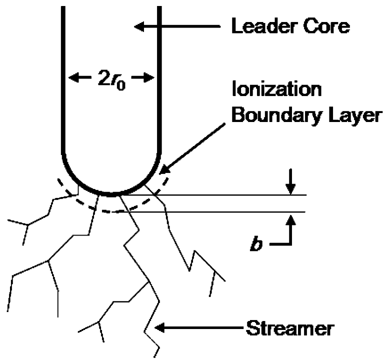

Fig. 1. Schematic representation of the leader-streamers system.

where E_{ci} is the corona inception field at the leader tip, which is determined by the initial radius r_0 of the leader core at continuous leader inception. Applying the streamer theory, the following relationship was obtained [6] between the corona inception field E_{ci} and the equivalent electrode radius of curvature r

$$E_{ci}(r) = 2300 \cdot [1 + 0.224/r^{0.37}] \quad (\mathrm{kV/m, m}) \tag{4}$$

with E_{ci} in kV/m and r in m. In this model it is further assumed that leader extension during propagation is due to intense ionization in a thin boundary layer ahead of the leader tip, as shown schematically in Fig. 1. The injection into the leader tip of a charge q per unit length will result in the increase of the conductance of the boundary layer from an initial value per unit length g_0 ahead of the leader tip to a value g_c corresponding to a critical volume conductivity σ_c characterizing the initial segment of the leader behind the leader tip. A quantity of interest is the thickness b of the boundary layer. In analogy with heat transfer and fluid dynamics [7], the thickness of the ionization boundary layer will be defined by

$$b = \alpha_e \Big/ \left| \frac{d\alpha_e}{dz} \right|_{z=0} \tag{5}$$

where z is the axial distance downstream from the leader tip, and

$$\alpha_e = \alpha - \eta \tag{6}$$

is the effective ionization coefficient at the leader tip. In this expression, α is the ionization coefficient and η is the attachment coefficient, both being functions of the reduced electric field $E(z)/p$, where p is the ambient pressure.

For creation of a segment of the leader equal to the thickness of the ionization boundary layer b, the amount of the injection charge involved will be bq. The relationship between this amount of charge and the initial and final conductances per unit length g_0 and g_c, respectively, will for simplicity be expressed as

$$b \cdot q = k_0(g_c - g_0). \tag{7}$$

In this expression, k_0 is Toepler's constant, which was initially introduced as an empirical constant [8] but was more recently given a simplified physical interpretation in terms of the ionization process [9]. In the spark theory of Weizel and Rompe the conductance per unit length depends on the internal energy rather than the charge [10]. As shown in the Appendix, using Weizel and Rompe's theory under a quasi-stationary current with $g_0 \ll g_c$, expression (7) will remain practically the same. We used the Toepler constant moreover because of the availability of reliable measurements [9]. In air at atmospheric pressure k_0 has been experimentally determined as 5×10^{-3} Vs/m [9].

For a newly formed leader segment, the voltage gradient starts at an initial value close to the streamer voltage gradient E_s (4–5 kV/cm) so that the leader current can be expressed as

$$i = g_c E_s = \pi r_0^2 \sigma_c E_s \tag{8}$$

where r_0 is the initial radius of the leader and σ_c is the critical volume conductivity.

Furthermore the leader current is related to the leader speed v and the injection charge q per unit length by

$$i = q \cdot v. \tag{9}$$

Substituting from (8) and (9) into (7), an expression of the leader speed is obtained

$$v = bE_s / [k_0(1 - g_0/g_c)] \tag{10}$$

where b is the thickness of the ionization boundary layer expressed by (5).

Under normal conditions, $g_0 \ll g_c$ so that (10) could be further simplified to

$$v = bE_s/k_0. \tag{11}$$

In the ionization boundary layer, in the immediate proximity of the leader tip, the reduced electric field will be initially high such that $E/p > 60$ V/cm · Torr, where attachment can be neglected. Based on measurements by Masch and Sanders, the following empirical expression [11] for the effective ionization coefficient can be used:

$$\alpha/p = 9.68 \exp(-264p/E) \tag{12}$$

with α in cm^{-1}, p in Torr (133.32 Pa), and E in V/cm.

For an electric field E_{ci} at the tip of the hemispherically caped cylindrical leader of radius r_0 (see Fig. 1), it can be easily shown that the electric field gradient amounts to $-2E_{ci}/r_0$. Using (12), expression (5) can be expressed as

$$b = 2.49 \times 10^{-8} r_0 \cdot E_{ci} \quad (\mathrm{m, V/m}) \tag{13}$$

with b in m, r_0 in m and E_{ci} in V/m.

An alternative approach that was explored for the determination of the thickness of the ionization boundary layer was to require that b satisfies the condition

$$\alpha_e \cdot b = 18 \tag{5a}$$

with α_e in m^{-1} and b in m, which resembles the criterion for creation of a critical avalanche. In (5a), α_e corresponds to the resultant electric field at the leader tip, $E_{ci}(r)$.

For a 10-m leader-plane gap and leader radii of curvature r in the range 0.8–2.4 mm (corresponding to overvoltages U/U_{lc} in the range 1.0–3.0, as shown in the next section), Table I shows

TABLE I
IONIZATION BOUNDARY LAYER THICKNESS FOR A 10-m GAP

U/U_{lc} (pu)	r (mm)	b (μm)	
		From (5)	From (5a)
1.0	0.8	190	202
1.5	1.2	256	260
2.0	1.6	316	314
2.5	2.0	373	365
3.0	2.4	427	414

a comparison between the values of b obtained from (5) and (5a), confirming good agreement of both approaches. We have however maintained the application of (5) from before.

It should be noted that the leader channel diameter grows with time (due to energy dissipation) and therefore measurements on a long air gap, depending on the measuring position, will tend to be higher than for shorter gaps [12]. Since we are here interested in the leader core diameter in the immediate vicinity of the leader tip, leader channel diameter measurements for shorter gaps will be more appropriate. Of particular interest are measurements under critical front impulses. Measurements at the University of Munich in a 1.5-m rod-plane gap gave leader channel diameter in the range of 1–2 mm, [12] i.e., r_0 in the range of 0.5–1.0 mm. Similar information on initial leader diameter was also obtained by Schlieren technique [13].

III. Effect of Overvoltage and Leader Current

Based upon experimental evidence in the laboratory, positive leader speed can be increased either by applying overvoltages to the air gap concerned [14] or by creating an electrically conducting filament along the path of the leader propagation [15]. The effect of the conducting laser filament on leader speed can in principle be accounted for by the increase of g_0/g_c in (10) but this however is outside the scope of the present paper. This section will therefore only address the effect of overvoltages and the resulting current increase on the positive leader speed.

With a voltage U applied to the leader tip, the leader corona charge can be expressed as [16]

$$Q(U) = A \cdot U(U - U_{ci}) \tag{14}$$

where A is in general a function of the distance from the leader tip to ground.

For leader corona, U is normally much larger than U_{ci} so that for any gap length the dependence of Q on U will approximately follow a quadratic law. Considering (1), Q can be expressed as

$$Q(U) = \frac{cU^2}{U_{lc}} = Q_0\left(\frac{U}{U_{lc}}\right)^2 \tag{15}$$

which means that Q will be proportional to the square of the overvoltage factor defined as U/U_{lc}, with U_{lc} a function of the gap length [5].

We will further assume that the initial leader (stem) cross section will be proportional to the streamer charge Q (leader corona). In [13] there is experimental evidence that the leader cross section is approximately proportional to the total injected charge. From the previous assumption and (15) above it follows that for any overvoltage factor U/U_{lc}:

$$r(U) = r_0(U/U_{lc}). \tag{16}$$

It also follows that at leader inception, the initial leader cross section will be proportional to the critical charge so that with view of (1):

$$r_0 = const \cdot \sqrt{U_{lc}}. \tag{17}$$

With a constant volume conductivity σ_c, the initial leader conductance per unit length will be proportional to the initial leader cross section, so that

$$i(U) = i_0(U/U_{lc})^2 \tag{18}$$

where i_0 is the continuous leader inception current, without overvoltage.

For any overvoltage factor U/U_{lc} and corresponding leader current $i(U)$, the ionization boundary layer thickness, following (13), will be:

$$b(U) = 2.49 \times 10^{-8} r(U) \cdot E_{ci}(r) \quad (\mathrm{m, V/m}) \tag{19}$$

with b in m, r in m, E_{ci} in V/m, and with $r(U)$ obtained from (16) with a known value of r_0.

At any overvoltage factor U/U_{lc}, the leader speed will be obtained by replacing b in (11) by $b(U)$

$$v(U) = b(U)E_s/k_0. \tag{20}$$

It should be emphasized that in the above analysis, U refers to the voltage applied to the leader tip. The total applied voltage normally referred to in laboratory experiments includes moreover the leader voltage drop. Furthermore, U_{lc} here refers to leader inception voltage of the gap extending from the leader tip to ground. At leader inception, there is no difference with the conventional definition. However, as the leader progresses into the gap the distance h from the leader tip to ground is progressively reduced with a corresponding reduction of $U_{lc}(h)$. The present definitions were adopted for simplicity and more importantly for ease of application for very long gaps associated with lightning.

IV. Numerical Evaluation and Comparison With Experiments

Since in initial leader channel diameter measurements by Les Renardières Group, [12] it was noted that any kind of distortion would produce an image broadening effect, we will adopt the minimum value of 0.5 mm for r_0 and a rod-plane gap of 1.5 m. Since according to [1] the leader inception voltage of a 1.5-m gap amounts to approximately 433 kV, the relationship between channel radius and the leader inception voltage for any gap length would be

$$r_0 = 0.5\sqrt{U_{lc}/433} \quad (\mathrm{mm, kV}) \tag{21}$$

with r_0 in mm and U_{lc} in kV.

TABLE II
SAMPLE RESULTS FOR A 10-m ROD-PLANE GAP

Continuous leader inception						
U_{lc} kV	r_0 mm	E_{ci} kV/cm	b μm	v_0 cm/μs	i_0 A	q_0 μC/m
1120	0.8	95	190	1.52	0.68	45
Under overvoltage						
U/U_{lc} pu	r mm	E_{ci} kV/cm	b μm	v cm/μs	i A	q μC/m
2.0	1.6	79	316	2.53	2.74	108

A sample model result is shown in Table II for a 10-m rod-plane gap both at continuous leader inception as well as under an overvoltage of 2 p.u. (with $E_s = 4\ \mathrm{kV/cm}$).

As shown in [1], the continuous leader inception voltage of a rod-plane gap of length d is given by

$$U_{lc} = 1556/(1 + 3.89/d) \quad (\mathrm{kV, m}) \tag{22}$$

with U_{lc} in kV and d in m.

With U_{lc} of 1120 kV [1], q_0 of 45 $\mu\mathrm{C/m}$ [2], $r_0 = 0.8$ mm, which results in E_{ci} of 95 kV/cm, boundary layer thickness b of 190 $\mu\mathrm{m}$ a leader speed v_0 of 1.52 $\mathrm{cm}/\mu\mathrm{s}$, is obtained in excellent agreement with experiment [2].

With an overvoltage factor of 2 defined here by U/U_{lc}, Table II shows an increased radius of the leader of 1.6 mm, a correspondingly reduced E_{ci} of 79 kV/cm, an increased ionization boundary layer thickness of 316 $\mu\mathrm{m}$, an increased leader speed of 2.53 $\mathrm{cm}/\mu\mathrm{s}$, a substantially increased leader current of 2.74 A and a leader charge per unit length which reaches 108 $\mu\mathrm{C/m}$.

It is generally accepted [1], [2] that for a rod-plane gap of length d tested with a switching impulse with a critical front without overvoltage, the positive leader penetrates the gap with practically constant tip potential equal to the continuous leader inception voltage $U_{lc}(d)$. As mentioned before, however, as the leader approaches the plane, the distance h from the leader tip to plane decreases continuously with corresponding decrease of the voltage $U_{lc}(h)$ needed for leader inception of such a gap. Therefore the ratio between the tip potential $U_{lc}(d)$ and $U_{lc}(h)$ will be greater than unity, providing a virtual overvoltage according to the definition of the present model. The model therefore predicts that even without application of an overvoltage to the high voltage electrode, the leader speed increases slightly as the leader progresses towards ground. This is shown in Fig. 2, for a 10-m rod-plane gap exposed to a critical positive switching impulse, for axial leader length up to 6.5 m. In the same range of the leader length the current increased in a range of 0.69–1.36 A.

For overvoltage factors in the range 1.0–2.4 p.u., Fig. 3 shows the variation of the leader current i for a 10-m rod-plane gap. The leader current i varies from approximately 0.7 A to 4.0 A. In the same overvoltage range the positive leader speed varies from 1.52 $\mathrm{cm}/\mu\mathrm{s}$ to 2.89 $\mathrm{cm}/\mu\mathrm{s}$, as shown in Fig 4, confirming that the leader current is much more sensitive to overvoltages than leader speeds [14]. Regression analysis (R square: 0.99999) in the same overvoltage range resulted in the following relationship between leader speed and leader current for the 10-m rod-plane gap under consideration:

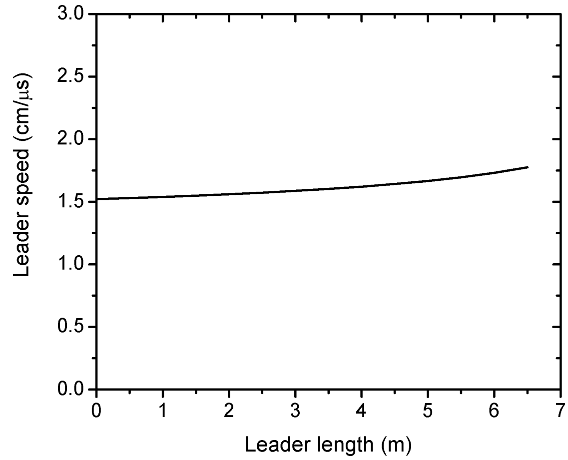

Fig. 2. Variation of leader speed with axial leader length for a 10-m rod-plane gap.

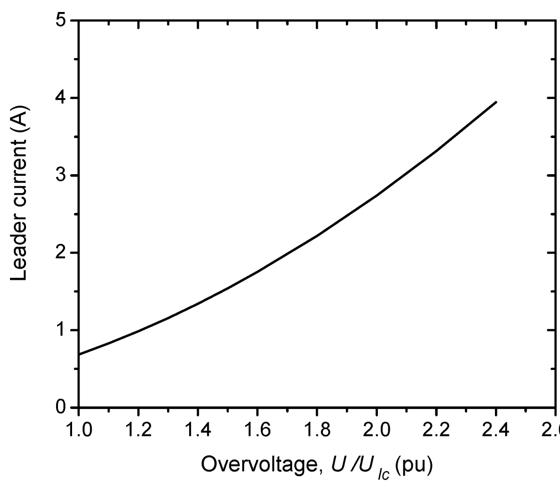

Fig. 3. Dependence of leader current on overvoltage for a 10-m gap.

$$v = 1.75 \times 10^4 \cdot i^{0.367} \quad (\mathrm{m/s, A}) \tag{23}$$

with v in m/s and i in A. Extending the overvoltage factor, for the 10-m gap, to cover the range 1.0–3.0 p.u., expression (23) remains practically unchanged. Expression (23) also proved to be rather insensitive to the gap length. For a 4-m rod-plane gap and overvoltages in the range 1.0–2.0 the exponent amounted to 0.364 and the speed corresponding to a leader current of 1 A amounted to 1.61×10^4 m/s.

The following empirical relationship by Hutzler [17] was based on measurements by Les Renardières Group:

$$v = 1.75 \times 10^4 \cdot i^{0.30} \quad (\mathrm{m/s, A}) \tag{24}$$

with v in m/s and i in A. Comparison between model results and the above empirical formula are shown in Fig. 5 and considered very satisfactory.

Regression analysis of model results (R square: 0.99999) for the 10-m gap also shows that dependence of the positive leader speed on the overvoltage factor defined before takes the form

$$v = 1.52 \times 10^4 (U/U_{lc})^{0.735} \quad (\mathrm{m/s}) \tag{25}$$

with v in m/s and U and U_{lc} in kilovolts. Finally, Fig. 6 shows the effect of gap length d on leader speed at inception for gaps

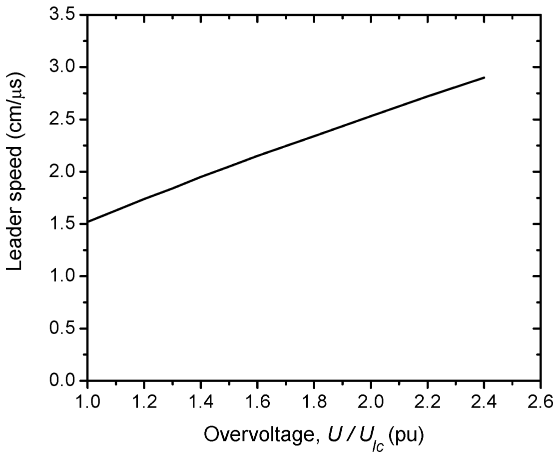

Fig. 4. Effect of overvoltage on leader speed for a 10-m gap.

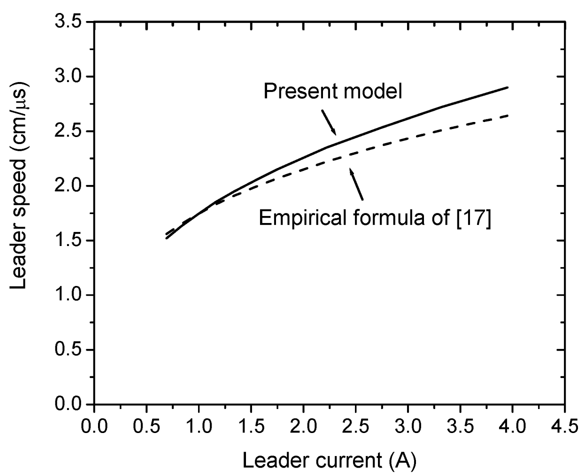

Fig. 5. Dependence of positive leader speed on current for a 10-m gap.

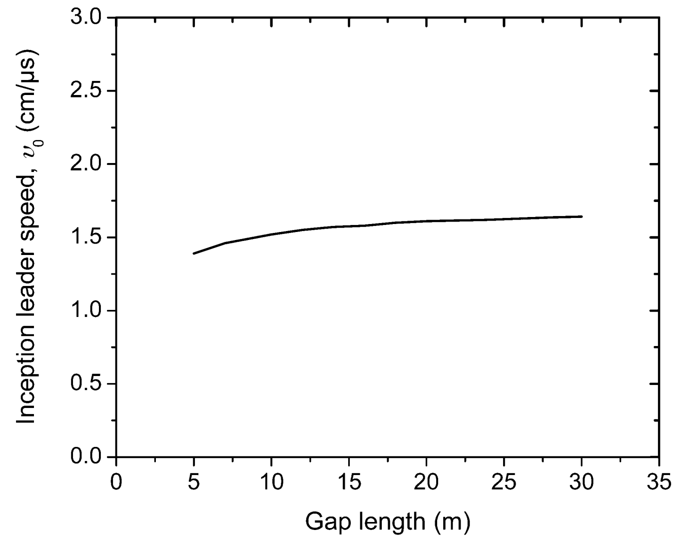

Fig. 6. Variation of inception leader speed with gap length.

in the range 5–30 m. It is shown, in agreement with experiment, [2] that the leader speed at inception varies in a limited range despite the wide range of gap lengths investigated. Note that for laboratory experiments on gaps of practical dimensions, the overvoltage factor, normally defined as the ratio between the test voltage and the 50% breakdown voltage [14] can only be varied within a limited range above which streamer breakdown of the gap takes place.

V. Conclusion

A new model for the speed of a positive leader discharge has been introduced and applied to long air gaps under critical switching overvoltages.

1) The model is based on intense ionization in a thin boundary layer ahead of the leader tip.
2) In order to replace any possible extinction of a streamer filament, the net electric field at the leader tip due to both the applied voltage and the charge of leader corona has to be maintained at or above the corona inception field.
3) The thickness of the ionization boundary layer has been defined by the ratio between the net ionization coefficient α_e and its space gradient $\mathrm{d}\alpha_e/\mathrm{d}z$ at the leader tip.
4) The transition from an initial conductance g_0 per unit length ahead of the leader tip to the critical conductance g_c per unit length of a newly formed leader segment is related to the injection of a certain amount of charge per unit length.
5) The radius of the leader channel (stem) in the proximity of the tip is determined by the charge of the leader corona, both at inception and under overvoltage conditions.
6) Evaluation of the positive leader speed at inception conditions for a 10-m rod-plane gap was found to be approximately 1.5×10^4 m/s, in excellent agreement with laboratory experiments under critical switching impulses.
7) For a rod-plane gap under critical switching impulse, the model shows that leader speed slightly increases from inception until the final jump is approached. In the same range leader current increases more significantly.
8) In agreement with the experiment, the leader current was found to be much more sensitive to the overvoltage factor (U/U_{lc}) than the leader speed.
9) The model shows that for laboratory gaps, the leader speed is proportional to the overvoltage factor raised to a power of approximately 0.73 and to the leader current raised to a power of 0.37, the latter is in good agreement with the experiment.
10) At leader inception the model shows, in agreement with experiment, that the positive leader speed is rather insensitive to the gap length which was varied in the range of 5–30 m.

Application of the model findings to an upward positive leader under lightning conditions will be the subject of a separate publication.

Appendix
Application of Weizel and Rompe Theory to the Ionization Boundary Layer

In the Weizel and Rompe theory [10], power dissipation accounts for the increase in the internal energy of the spark channel (losses neglected)

$$\frac{i^2}{\pi r^2 \sigma} = \frac{d}{dt}(\pi r^2 u) \tag{26}$$

where i is the current at any instant, r is the channel radius, σ is the electrical conductivity of the channel, u is the internal energy per unit volume.

Simplified analysis by Weizel and Rompe led to the following relationship between σ and u:

$$\sigma = au/p \tag{27}$$

where p is the ambient pressure and a is the Weizel and Rompe's spark constant, which is independent of the pressure.

Considering the conductance per unit length

$$g = \pi r^2 \sigma \tag{28}$$

and substituting in (26) from (27) and (28), we obtain

$$\frac{i^2}{g} = \frac{p}{a}\frac{dg}{dt}. \tag{29}$$

Integrating (29) for a constant current from the initial value g_0 to the critical value g_c

$$i^2 \cdot \Delta t = \frac{p}{2a}\left(g_c^2 - g_o^2\right) \tag{30}$$

where Δt is the time step for the leader to span the ionization boundary layer of thickness b.

Since the injected charge per unit length is q, it follows that:

$$q \cdot b = i \cdot \Delta t. \tag{31}$$

Recognizing that $g_0 \ll g_c$, it follows from (30) and (31) that:

$$i \cdot q \cdot b = \frac{p}{2a} g_c (g_c - g_o). \tag{32}$$

Multiplying both sides of (32) by the initial leader gradient E_s and recognizing from (8) that

$$i = g_c E_s \tag{33}$$

(32) becomes

$$q \cdot b = \frac{p}{2aE_s}(g_c - g_o) \tag{34}$$

which is identical to (7) with Toepler's constant k_0 being replaced by $p/(2aE_s)$.

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